NETWORK PERFORMANCE UNDER LINK DISRUPTIONS: A COMPARISON OF TWO-WAY AND ONE-WAY NETWORK CONFIGURATIONS

By

Zhengyao Yu*
Department of Civil and Environmental Engineering
The Pennsylvania State University
201 Transportation Research Building
University Park, PA 16802
Phone: 814-863-1897
zuy107@psu.edu

Vikash V. Gayah
Department of Civil and Environmental Engineering
The Pennsylvania State University
231L Sackett Building
University Park, PA 16802
Phone: 814-865-4014
gayah@engr.psu.edu

***Corresponding Author**

November, 2018

INTRODUCTION

Since the existence of well-defined relationships between aggregated traffic parameters in urban areas was recently verified (*1*, *2*), several studies have used this approach to compare the operational performance of different network configurations (*3*–*6*). For example, although one-way streets provide higher roadway capacities and operating speeds (*7*–*10*), recent studies have revealed that two-way street networks can yield higher network output due to the more direct routing when trips are short. Furthermore, two-way street networks in which left turns are restricted have been found to provide an ideal comprise between efficient intersection operations and vehicle routing (*4*–*6*).

However, little attention has been paid to these street networks' performance under non-recurring and unexpected disruptions, which contribute to about 40 percent of urban congestion (*11*). If some configurations are more robust to such disruptions, a significant portion of urban congestion might be alleviated or even eliminated by the network itself. A recent study by the authors analyzed the performance of two-way networks after link disruptions under light traffic (*12*). However, this study simplifies the problem by assuming a low-traffic situation and applying a non-time-variant distance-based route choice method. The results thus do not represent situations with medium to high traffic demands.

This present work continues the comparison among different network configurations – specifically, two-way (TW), two-way without left turns (TWL), and one-way (OW) – with moderately congested traffic conditions. The Link Transmission Model, which is a numerical solution to the kinematic wave theory (KWT) model, is applied in which vehicles dynamically select their routes based on their prevailing travel times. Aggregated traffic metrics, including the Macroscopic Fundamental Diagram (MFD), are used to evaluate network performance when links are disrupted, both when vehicles have prior knowledge of the disruption and when they do not. The results provide more insightful comparisons regarding networks' resilience to disruptions under more realistic traffic situations.

METHODOLOGY

Link Transmission Model

A numerical solution for KWT that can accurately capture queue spillovers inside a network – the Link Transmission Model (LTM) (*13*) – is used in this study. Unlike the Cell Transmission Model (*14*), the LTM calculates flows for each link rather than for cells inside a link and therefore has much lower computational requirements. The experiments here are performed based on a MATLAB toolbox that implements the LTM (*15*). At each time step, the LTM updates the cumulative vehicle counts at both upstream and downstream ends of each link. Like any KWT-based model, LTM does not track the movement of individual vehicles. Instead, vehicles on links are grouped by their destinations and are routed using an all-or-nothing assignment. In addition, conflicts at intersections cannot be explicitly modeled in the LTM framework, although it is possible to set discounted capacities for movements that yield to others. Readers are referred to (*13*) for more details about the model.

Aggregated traffic metrics

Aggregated network traffic metrics (*1*, *2*) are used as a tool to evaluate network operation. Network-level operational metrics such as average flow, average density, accumulation, and trip completion rate are directly obtained from the LTM outputs, and metrics such as average trip time and trip length are indirectly computed based on these.

Network setup and vehicle routing

Experiments in this paper are performed in a 10×10 grid network with 0.2-mile-long blocks. The time-step for updating vehicle counts within the LTM is set to 10 seconds. The three network configurations (TW, TWL, and OW) are compared under homogeneous demands where vehicles enter and exit networks at mid-block locations. To ensure all trips can get to their destinations even under link disruptions, the most outside ring of the network operates without movement restrictions (i.e. TWL or OW).

Each lane in the network is assumed to obey the same triangular fundamental diagram with free-flow speed of 32 mph, capacity of 1600 veh/hr/lane, and jam density of 200 veh/mi/lane. The ratio of backward wave speed (8 mph) and free-flow speed is an integer under this setting, which ensures exact analytical solution from the LTM (*13*). All roadway segments are assumed to have two lanes. In the TW and TWL networks, there is one lane traveling in each direction; in the OW networks, two lanes travel in the same direction. A signal plan of 60-second cycles with equal splits for north-south and west-east movements is applied to all intersections without coordination (0 offset). Although coordination change traffic performance on an arterial, a recent study showed that coordination on a two-dimensional grid network does not significantly change overall performance (*16*).

Every two cycles, the Dijkstra's algorithm is implemented at each node to identify the shortest paths to all other nodes based on links' mean travel time in the past two cycles. The free-flow speed of any disrupted link is set to an extremely low value to mimic closure. Two types of disruptions are modeled in this work: those in which road users know about the disruption ahead of time (prior-knowledge, PK) and those in which road users learn of the disruption only after they reach a nearby intersection (no-prior-knowledge, NPK). To simulate such behaviors in the LTM, the vehicles on each link are further grouped by their knowledge about the disruption. Two sets of routing paths are separately derived for the aware and unaware groups. Road users unaware of the disruptions enter the aware group when they reach a nearby intersection.

FINDINGS

For each case, simulations are run for 120 minutes with incremental homogeneous demands in the first 90 minutes followed by a 30-minute unloading process. During the first 60 minutes, the network demand increases at 15-minute time intervals with steps of 4000 veh/hr. The highest demand level (20000 veh/hr, which exceeds the capacity of the lowest performing networks) lasts for 30 minutes and then the network begins to unload at 90 minutes.

The three network configurations are iteratively tested with one internal link disrupted. The rest of the section will discuss network performance before (45 minutes) and after (90 minutes) the high demand periods in each case.

Scenario 1: Prior-knowledge (PK) link disruptions

Under prior-knowledge link disruptions, road users are aware of the disruption during their entire trip and make appropriate detours before reaching the disrupted link. Table 1 provides the mean values and standard deviations (in parentheses) for the operational metric during disruptions, aggregated across all links inside each network type.

Table 1 Summary of operation under PK link disruptions

(a) Calculated at time point 45 minutes

	Trip length	Trip time	Turn count	Max. accumulation	Max. trip completion rate
TW	5.09 (0.02)	2.85 (0.04)	2.17 (0.03)	569.69 (5.22)	12018.98 (43.89)
TWL	6.09 (0.04)	3.43 (0.03)	1.85 (0.02)	686.62 (5.61)	11997.71 (12.40)
OW	7.27 (0.04)	3.99 (0.04)	2.87 (0.02)	803.11 (6.64)	12006.96 (52.41)

(b) Calculated at time point 90 minutes

	Trip length	Trip time	Turn count	Max. accumulation	Max. trip completion rate
TW	10.52 (0.65)	19.79 (2.12)	2.26 (0.04)	3489.21 (205.61)	16509.10 (510.94)
TWL	6.41 (0.08)	4.21 (0.10)	1.93 (0.02)	1401.08 (26.71)	20482.91 (130.00)
OW	7.98 (0.31)	6.80 (0.80)	2.88 (0.02)	2178.41 (183.66)	18946.76 (549.73)

Although TW networks operate well under light demands (since it allows the most flexible routing), it appears that conditions degrade quickly as congestion evolves. This phenomenon is also observed in the undisrupted TW network. By comparison, TWL and OW networks accommodate the PK disruption much better, partly due to their higher capacities. This is especially true for the TWL network, as indicated by the lowest standard deviation values for all metrics.

Figure 1 provides heat maps illustrating the operational metrics after the disruption on the associated link. PK disruptions in the center of TW networks are well accommodated (illustrated by its relatively low trip lengths, trip times, and maximum accumulations in Figure 1b). Although a high amount of traffic uses the central area in the TW network, much of it can use another alternative when a central link is disrupted since multiple shortest-distance routes exist for most OD pairs. In comparison, impacts of disruptions inside the TWL network are more evenly distributed, partly because of its high capacity but also due to the lack of redundancy inside the routing choices. OW appears to lie somewhere in-between.

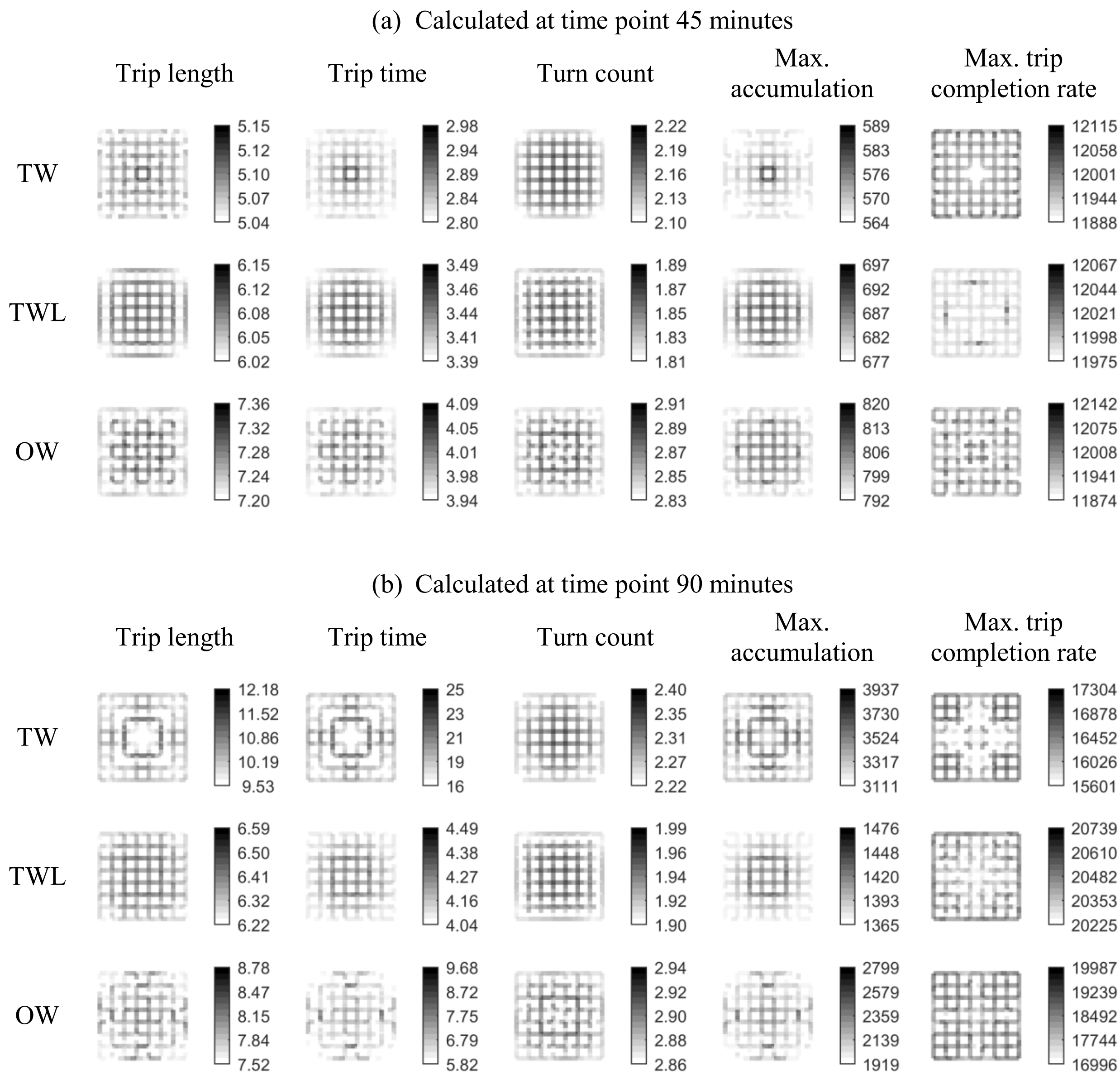

Figure 1 Network operation under PK disruptions

Scenario 2: No-prior-knowledge (NPK) link disruptions

In the second set of experiments, vehicles are not informed of the disruption in advance; thus, a high concentration of detour traffic occurs near the disrupted link as road users only become aware that the link is disrupted when they approach it. Table 2 provides a summary of the network performances.

Table 2 Summary of operation under NPK link disruptions

(a) Calculated at time point 45 minutes

	Trip length	Trip time	Turn count	Max. accumulation	Max. trip completion rate
TW	5.13 (0.04)	2.88 (0.08)	2.22 (0.06)	575.67 (13.40)	12017.33 (53.90)
TWL	6.20 (0.09)	3.53 (0.08)	1.95 (0.05)	703.63 (14.29)	11962.68 (42.95)
OW	7.40 (0.12)	4.13 (0.17)	2.94 (0.06)	828.56 (30.85)	11982.55 (107.44)

(b) Calculated at time point 90 minutes

	Trip length	Trip time	Turn count	Max. accumulation	Max. trip completion rate
TW	11.05 (1.03)	21.92 (4.60)	2.30 (0.06)	3595.42 (411.71)	16408.21 (872.78)
TWL	6.58 (0.17)	4.44 (0.25)	2.03 (0.05)	1469.75 (69.98)	20378.97 (185.66)
OW	8.60 (1.00)	8.41 (2.82)	2.91 (0.03)	2453.61 (473.32)	18345.81 (1021.30)

Under the NPK disruptions, although TWL and OW networks still perform better than the TW network, the OW network shows the highest operational degradation measured by the operational metrics when compared to PK disruptions. This is believed to be a consequence of movement restriction inside OW networks. When road users encounter the link disruption at a nearby intersection, it usually requires a long detour, which causes a quick spread of congestion near the disrupted links. On the other hand, movement restrictions in the TWL network cause long detours as well, but higher capacity in the TWL network provides a better resilience in the experiments.

For more details, Figure 2 provides heat maps for the disruption without prior knowledge. In this case, all network configurations are most sensitive to disruptions in the center as the highest amount of traffic use the area and disruptions without prior knowledge cause a concentration of detour inside the busy area. The trip times in the TW and OW networks show significant increases compared to the PK removal results, and a wider range of link disruptions cause severe impacts.

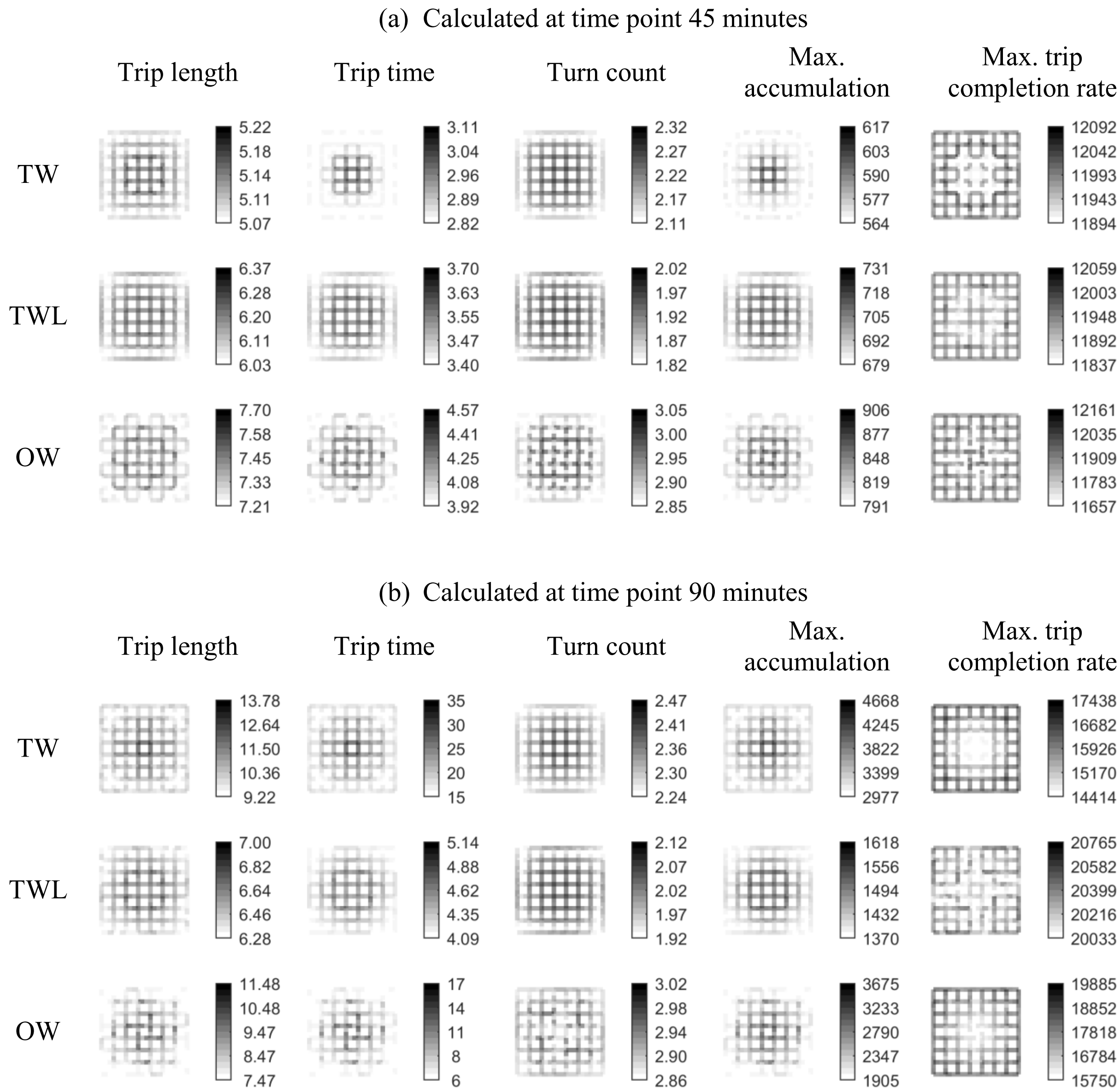

Figure 2 Network operation under NPK disruptions

CONCLUDING REMARKS

This paper compares the performance of three network configurations under link disruptions. The LTM is applied to abstract grid networks and network performance is tested under both PK and NPK disruptions. With more realistic traffic settings and routing rules, this represents an extension of an earlier work by the authors (*12*) where a simplified analytical procedure is applied under light traffic.

Overall, TWL networks are found to have the highest capacity among the three configurations tested. For this reason, TWL network remains uncongested throughout the experiments, even during NPK disruptions. TW networks perform well under low demand, but are naturally inefficient and therefore become the most congested. Disruptions in the central area can especially cause severe negative impacts in the TW network. The performance of the OW networks lies somewhere in-between the TW and TWL networks, but it shows the highest operational degradation under NPK disruptions, which indicates resilience issues of the network configuration.

This work is limited by the routing and intersection settings allowed in the LTM. Future work will compare network performance in more realistic settings in micro-simulation. More details about intersection control and geometry will be added and vehicles will be routed in a more realistic way. Mitigation strategies to combat link disruptions will then be studied analytically and tested in the microscopic simulation.

ACKNOWLEDGEMENT

The research was supported by NSF Grant CMMI-1749200.

REFERENCES

1. Geroliminis, N., and C. F. Daganzo. Macroscopic modeling of traffic in cities. Presented at *TRB 86th Annual Meeting*, Washington D.C., DC, 2007.
2. Geroliminis, N., and C. F. Daganzo. Existence of urban-scale macroscopic fundamental diagrams: Some experimental findings. *Transportation Research Part B: Methodological*, Vol. 42, No. 9, 2008, pp. 759–770.
3. Gayah, V. V, and C. F. Daganzo. Analytical Capacity Comparison of One-Way and Two-Way Signalized Street Networks. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2301, 2012, pp. 76–85.
4. Ortigosa, J., M. Menendez, and V. V. Gayah. Analysis of Network Exit Functions for Various Urban Grid Network Configurations. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2491, No. 15–2886, 2015, pp. 12–21.
5. Ortigosa, J., V. V. Gayah, and M. Menendez. Analysis of one-way and two-way street configurations on urban grid networks. *Transportmetrica B: Transport Dynamics*, Jun. 2017, pp. 1–21.
6. DePrator, A., O. Hitchcock, and V. Gayah. Improving urban street network efficiency by prohibiting left turns at signalized intersections. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2622, 2017, pp. 58–69.
7. Murphy, C. J. Baltimore's one-way streets. *Traffic Quarterly*, Vol. 4, No. 3, 1950, pp. 274–284.
8. Enustun, N. *Study of the Operational Aspects of One-Way and Two-Way Streets*. 1969.
9. Edwards, J. D. Traffic issues for smaller communities. *ITE Journal (Institute of Transportation Engineers)*, Vol. 68, No. 8, 1998, pp. 30–33.
10. Pline, J. *Traffic engineering handbook*. Prentice Hall, Englewood Cliffs, New Jersey, 1992.
11. Cambridge Systematics. Traffic Congestion and Reliability: Linking Solutions To Problems. 2004.
12. Yu, Z., and V. V Gayah. Comparison of Urban Street Network Resilience for Grid

Networks with and Without Left-Turning Maneuvers Under Light Traffic Situations. Presented at *Transportation Research Board 97th Annual Meeting*, Washington DC, United States, 2018.

13. Yperman, I., S. Logghe, and B. Immers. The Link Transmission Model: An Efficient Implementation of the Kinematic Wave Theory in Traffic Networks. Presented at *Advanced OR and AI Methods in Transportation, Proceedings 10th EWGT Meeting and 16th Mini-EURO Conference*, 2005.

14. Daganzo, C. F. The cell transmission model: A dynamic representation of highway traffic consistent with the hydrodynamic theory. *Transportation Research Part B*, Vol. 28, No. 4, 1994, pp. 269–287.

15. Himpe, W., R. Corthout, and M. J. C. Tampère. An efficient iterative link transmission model. *Transportation Research Part B: Methodological*, Vol. 92, 2016, pp. 170–190.

16. Girault, J.-T., V. V. Gayah, I. Guler, et al. Exploratory Analysis of Signal Coordination Impacts on Macroscopic Fundamental Diagram. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2560, 2016, pp. 36–46.